

# Low and High Surface Brightness Galaxies at Void Walls

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19 July 2012

## ABSTRACT

We study the relative fraction of low and high surface brightness galaxies (LSBGs and HSBGs) at void walls in the SDSS DR7. We focus on galaxies in equal local density environments. We assume that the host dark-matter halo mass (for which we use SDSS group masses) is a good indicator of local density. This analysis allows to examine the behavior of the abundance of LSBG and HSBG galaxies at a fixed local density and distinguish the large-scale environment defined by the void geometry. We compare galaxies in the field, and in the void walls; the latter are defined as the volume of void shells of radius equal to that of the void. We find a significant decrement, a factor  $\sim 4$ , of the relative fraction of blue, active star-forming LSBGs in equal mass groups at the void walls and the field. This decrement is consistent with an increase of the fraction of blue, active star-forming HSBGs. By contrast, red LSBGs and HSBGs show negligible changes. We argue that these results are consistent with a scenario where LSBGs with blue colors and strong star formation activity at the void walls are fueled by gas from the expanding void regions. This process could lead to LSBG to HSBG transformations.

**Key words:** large scale structures: voids, galaxy groups, statistical, LSB galaxies

## 1 INTRODUCTION

The large-scale environment, and in particular void walls, may have significant effects on the galaxy properties and their evolution. It is well known that galaxy properties, such as morphology, star formation rates and colours, vary strongly with the galaxy density in their local environment (Dressler 1980; Lewis et al. 2002; Kauffmann et al. 2004). These variations are related to significant differences in how the evolution of galaxies varies with the environment, mainly due to interactions, merger histories, and assembly bias (e.g. Moore et al. 1998; Bell et al. 2006).

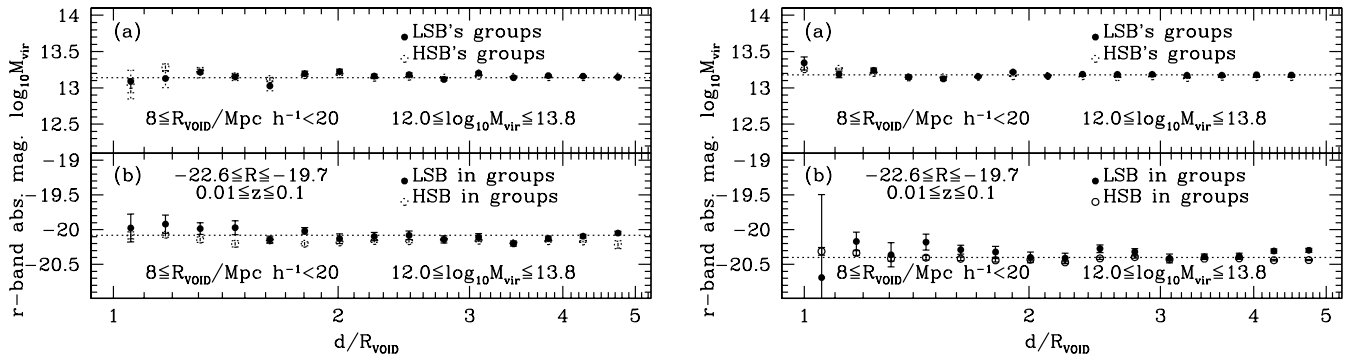
It is expected that galaxies in voids have significantly different star formation and chemical enrichment histories in comparison to those of galaxies in denser environments (see, e.g., Peebles 2001; Gottlöber et al. 2003; Hoeft et al. 2006; Hahn et al. 2007, 2009, and references therein). It is well established that the highest surface brightness galaxies reside in high density environments. However, the issue of the typical environment of low surface brightness galaxies (LSBGs hereafter) is not completely settled albeit some authors suggest LSBGs populate preferentially lower density environments (see for instance Rosenbaum et al. 2009, Galaz et al. 2011)

LSBGs represent an important population among ex-

tragalactic objects. The central surface brightness of the disk in the B-band,  $\mu_0(B)$ , is the photometric parameter typically used to separate the high and the low surface brightness regime of galaxies. The most common threshold values found in the literature are between 22 and 23 mag arcsec<sup>2</sup> (Impey et al. 2001).

LSBGs are characterized by many interesting observational properties such as a low density of stars, which produce the low surface brightness. They also present extended flat rotation curves (de Blok 2005; Swaters, Sanders & McGaugh 2010) having one of the highest M/L ratios in the Universe (Sprayberry et al. 1995).

The low star formation rate in combination with their rather isolated location in the cosmic web (Rosenbaum et al. 2009), as reported by several authors, give clues for the understanding of their formation and evolution. Several results provide evidence that large scale underdense regions, like cosmological voids, are characterized by coherent outflows of mass and galaxies moving toward the void edges (Ceccarelli et al., 2006, Padilla et al., 2005). Consequently galaxies at void edges or walls have undergone different evolutionary and merger histories than their field counterparts. This could be due, for instance, to the void material accumulating around them, or to the fact that void galaxies most likely spent their lives inside voids.



**Figure 1.** *Left* (a) Median virial masses for selected groups hosting at least one blue,  $u-r \leq 2.2$ , LSB (filled circles) and HSB (open circles) galaxy as a function of normalized void-centric distance, for void radii in the range  $8 h^{-1} \leq R_V < 20 h^{-1} \text{Mpc}$  and group virial masses within  $10^{12.0}$  and  $10^{13.8} M_{\odot}$ . (b) Median absolute magnitude of blue LSB (filled circles) and HSB (open circles) galaxies in groups as a function of normalized void-centric distance, for void radii and group virial masses in the same ranges. *Right* (a) Median virial masses for selected groups hosting at least one star-forming,  $e_{\text{class}} \leq -0.1$ , LSB (filled circles) and HSB (open circles) galaxy as a function of normalized void-centric distance. (b) Median absolute magnitude of star-forming LSB (filled circles) and HSB (open circles) galaxies in groups as a function of normalized void-centric distance.

Previous results have shown that galaxies at void walls present particular properties, such as in Ceccarelli, Padilla & Lambas (2008). Several studies have been focused on the properties of galaxies in underdense regions. The luminosity function of galaxies in voids has been measured by Rojas et al. (2005), who also study their photometric properties finding that the population of galaxies in voids is characterised by a fainter characteristic luminosity although the relative importance of faint galaxies is similar to that found in the field. Spectroscopic properties of void galaxies have also been studied in detail (Hoyle, Vogeley & Rojas, 2005); these results indicate that galaxies inside voids have higher star formation rates than galaxies in denser regions and are still forming stars at the same rate than in the past.

Several authors suggest that LSBGs would be more isolated than HSBGs at small scales (less than 2 Mpc, Bothun et al. 1993), and also between 2 Mpc and 5 Mpc (Rosenbaum et al. 2009). More recently, Galaz et al. (2011) found a deficit of neighbors for LSBGs at very small scales (less than 1 Mpc). These results motivate the formulation of the following questions: Is the large-scale low density environment, characteristic of voids, important for the set of LSBG properties? Can we find any signature in LSBGs residing in void walls?

Motivated by these facts, in this letter we perform a statistical study of galaxies in void wall and in the field in the SDSS, ensuring that their local environments traced by the mass of their host groups is the same, and analysing the fraction of blue, star-forming galaxies in equal local environments given the well known dependence on luminosity/stellar mass and local density (Balogh et al., 2004, Baldry et al., 2006, Dekel & Birnboim, 2006, Kannappan 2004, Lagos et al., 2008).

## 2 DATA SAMPLES

### 2.1 LSB and HSB galaxies

The galaxies studied in this work were extracted from the Main Galaxy Sample (Strauss et al. 2002) of the Sloan Dig-

ital Sky Survey data release 7 (SDSS DR7). The SDSS is the largest survey carried out so far covering  $10^4$  square degrees and containing CCD imaging data in five photometric bands (*ugriz*, Fukugita et al., 1996). The SDSS DR7 spectroscopic catalogue (Abazajian et al. 2009) comprises 929,555 galaxies with a limiting magnitude of  $r \leq 17.77$  mag. Within this magnitude limit, Strauss et al. (2002) find that 99% of the galaxies have half-light surface brightness brighter than  $23 \text{ mag arcsec}^{-2}$  in *r* and only  $\sim 0.01\%$  of galaxies are fainter than  $24.5 \text{ mag arcsec}^{-2}$  in *r*.

For a detailed description of how we select our sample we refer to Galaz et al. (2011). Essentially, we select late-type ( $\text{fracDevr} \leq 0.9$ ), nearly face on ( $b/a < 0.4$ ) galaxies in the redshift range  $0.01 \leq z \leq 0.1$  (we choose the lower cut to prevent peculiar velocity problems). For each galaxy, we calculate the surface brightness in the *B*-band using the band conversion from Smith et al. (2002). We correct the surface brightness for cosmological dimming. Finally, we use  $\mu_0(B) = 22.5 \text{ mag arcsec}^{-2}$  as the surface brightness cut to distinguish between LSB and HSBGs.

Since the SDSS is a magnitude-limited survey the observed populations of galaxies are not the same at different redshifts. This prevents us to compare in a statistical way properties of nearby galaxies with those situated at further distances. In fact, the faintest galaxies are only registered at small redshifts while the brightest galaxies cover the whole catalogue. This magnitude-limited selection introduces a luminosity bias which can be removed by constructing a volume-limited catalogue, defining redshift and luminosity ranges where the absolute magnitude distributions are the same for all the galaxy populations. A volume-limited catalogue allows us to compare two populations of LSBGs and HSBGs having the same absolute magnitude range, which for  $z \leq 0.1$  is  $M_r \geq -19.7$ .

### 2.2 Environmental information from SDSS galaxy group membership

We use the galaxy group catalogue of Zapata et al. (2009) in order to characterize the local environment of the galaxies

in our samples. As was shown by González & Padilla (2009), Pasquali et al. (2009), and Padilla, Lambas & González (2010), the mass of the host dark-matter halo is one of the best tracers of variation of galaxy properties with the environment. Therefore, we choose this parameter to this end, and use the luminosity of the four brightest members of the host group as a tracer of its mass (see for instance, Eke et al., 2004).

The groups in the Zapata et al. catalogue are identified using a friends of friends algorithm with varying projected linking length  $\sigma$  with  $\sigma_0 = 0.239h^{-1}\text{Mpc}$ , and a fixed radial linking length  $\Delta v = 450 \text{ kms}^{-1}$ , which provide a 95 percent complete sample with  $< 8$  percent contamination. The minimum number of members per group is 10, with virial masses calculated using the gapper estimator for the virial radius.

The dark-matter mass of the host halo of a galaxy is that of a galaxy group that lies within a projected distance of  $2h^{-1}\text{Mpc}$  and a velocity difference of  $800 \text{ kms}^{-1}$ . If no group satisfies this condition, the host halo mass is assumed to fall below the completeness limit of the group catalogue.

### 2.3 Identification of voids in the galaxy distribution

We define a void as the largest spherical volume within which the density is below a critical value and we follow the procedure described in Ceccarelli et al. (2006) to identify them in galaxy catalogues. The algorithm used to found voids can be briefly described as follows: First, we set a large number of random positions (for void centre candidates) distributed throughout the catalogue. For each random position we consider the larger sphere satisfying the condition  $\delta_{gx} < \delta_{max}$ , where  $\delta_{max}$  is the maximum density contrast allowed, and all the spheres considered are selected as void candidates. Finally, if there are superimposed void candidates, all of them are removed and the only one considered as a void is the largest underdense sphere, which should contain the others.

We apply the void finding algorithm to our volume limited sample of SDSS DR7 galaxies. We set  $\delta_{max} = -0.9$ , this value is in agreement with the mean density contrast of voids identified in the literature (Hoyle & Vogeley 2004, Patiri et al. 2006a). However, small variations on  $\delta_{max}$  do no affect the void statistics (Padilla et al. 2005). We have adopted  $z = 0.10$  as the limiting redshift of our sample. This choice of maximum redshift is a compromise between well-resolved voids which require faint galaxies, and a sufficiently large volume in order to have enough void statistics. The adopted absolute magnitude limits imply that the galaxy number density is high enough to lower the effects of shot noise in the identification of small voids. Our resulting sample, containing 184 voids, is restricted to radii within the range  $8$  to  $20h^{-1}\text{Mpc}$ , which comprises the best resolved systems suitable for our study. We use the normalized void-centric distance ( $d/r_{\text{void}}$ ) and define the void walls by the range  $0.9 < d/r_{\text{void}} < 1.2$ .

## 3 LSB GALAXIES IN GROUPS AT VOID WALLS

### 3.1 Properties of group LSB and HSB galaxies as a function of voidcentric distance

Given the well documented dependence of galaxy properties on local density, we study galaxies in equal mass groups, as this ensures an equal local environment (Pasquali et al., 2009, Padilla, Lambas & González, 2010). We select group samples with equal distributions of virial masses at different void-centric distances. These samples allow an analysis of the properties of LSBGs in groups at void walls and a proper comparison to LSBGs in similar environments beyond the void walls. This procedure should help to disentangle the relative weights of large scale (void walls) and local effects (group) on LSBG properties. We use k-corrected  $u-r$  colors (to  $z = 0.1$ ) and the parameter *eclass* to classify the galaxies. *eclass* represents the projection of the first three principal components of the galaxy spectrum, and ranges from  $-0.35$  to  $0.5$  corresponding to the sequence of passive to strongly star forming galaxies. The top left panel in Figure 1 shows the mean virial mass of SDSS DR7 selected groups containing at least 1 blue ( $u-r \leq 2.2$ )<sup>1</sup> LSBG (HSBG) in filled (open) circles, as a function of normalized distance to the void centre. The mean virial mass of SDSS DR7 selected groups containing at least 1 star-forming LSBG or HSBG (*eclass*  $\leq -0.1$ ) is shown in the top right panel. As can be seen the mean virial mass of the samples shows similar values over the full range of void-centric distances. This assures that, on average, the local environments of our sample of LSBGs remain similar across the void walls.

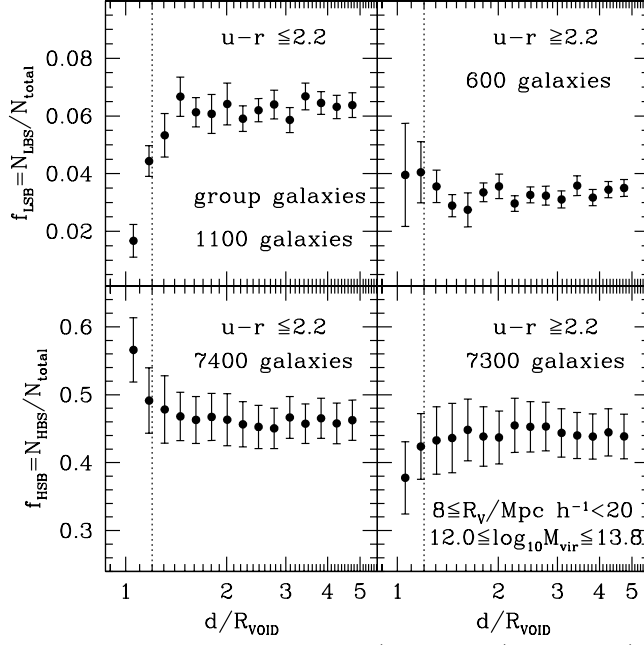
Given that the distribution of LSB galaxies could exhibit a dependence on luminosity and local density, we have explored the mean  $M_r$  magnitude of LSBGs for group galaxies in void walls and outside voids separately. The bottom left panel in Figure 1 shows the mean r-band absolute magnitude for blue ( $u-r \leq 2.2$ ) LSBG (filled circles) in groups as a function of normalized distance to the void centre; open circles correspond to blue HSBGs in groups. The corresponding mean magnitude for star-forming LSBGs and HSBGs is shown in the bottom right panel. As can be seen the mean luminosity of group LSBG and HSBG samples is nearly constant for galaxies in the void walls and in the field. Thus, differences in the properties of LSBGs and HSBGs should mainly be related to the astrophysical effects associated to the special star formation history of galaxies which today reside within void walls and the field.

### 3.2 Relative abundances of galaxies according to color and spectral type

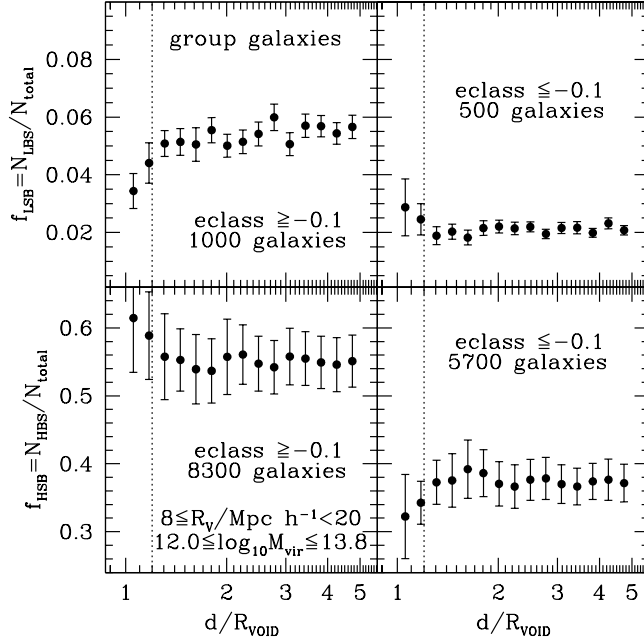
We analyse the relative fraction of LSBGs and HSBGs in groups at different distances from void centres, taking into account their k-corrected  $u-r$  colors (to  $z = 0.1$ ).

The results are shown in Figure 2, where it can be appreciated that the sample of HSBGs (lower panels) shows the well documented behaviour that bluer galaxies occupy preferentially the void neighbourhoods.

<sup>1</sup> The color and *eclass* adopted cuts divide the samples into the red and blue (and active and passive star formation) populations.



**Figure 2.** Left: Relative fraction of blue,  $u-r \leq 2.2$ , LSB (upper panel) and HSB (lower panel) galaxies in groups as a function of normalized void-centric distance. Right: Relative fraction of red,  $u-r \geq 2.2$ , LSB (upper panel) and HSB (lower panel) galaxies in groups as a function of normalized void-centric distance. Void radii are in the range  $8 h^{-1} \leq R_V < 20 h^{-1} \text{Mpc}$  and group virial masses within  $10^{12.0}$  and  $10^{13.8} M/M_\odot$ . The dotted lines indicate the outer boundary of the void wall.



**Figure 3.** Left: Relative fraction of star-forming,  $\text{eclass} \geq -0.1$ , LSB (upper panel) and HSB (lower panel) galaxies in groups as a function of normalized void-centric distance. Right: Relative fraction of non star-forming,  $\text{eclass} \leq -0.1$ , LSB (upper panel) and HSB (lower panel) galaxies in groups as a function of normalized void-centric distance. Void radii are in the range  $8 h^{-1} \leq R_V < 20 h^{-1} \text{Mpc}$  and group virial masses within  $10^{12.0}$  and  $10^{13.8} M/M_\odot$ . The dotted lines indicate the outer boundary of the void wall.

The left panels in Figure 2 show the relative fraction of LSBGs (upper panel) and HSBGs (lower panel) in groups, corresponding to blue objects ( $u - r < 2.2$ ). It can be seen that at the void walls there is a strong systematic drop in LSBG fraction (upper panel), whereas the fraction of HSBGs increases (lower left panel of Figure 2), at a fixed local den-

sity (Ceccarelli, Padilla & Lambas 2008, González & Padilla 2009).

The right panels in Figure 2 show the relative fraction of LSBGs (upper panel) and HSBGs (lower panel) in groups, corresponding to red objects ( $u - r > 2.2$ ). As can be appreciated we obtain similar fractions of red LSB and HSB galaxies over the full range of void-centric distances. From a

more detailed analysis of the lower right panel of Figure 2 it can be noticed a slight drop on the fraction of red HSBGs in groups at void walls. However, in general, the mean fraction of group LSBG and HSBG samples is nearly constant for red galaxies in the void walls and in the field.

We have also examined the star formation activity of these LSB galaxies at void walls through the *eclass* parameter. In Figure 3 we present the relative fraction of LSB and HSB galaxies considering high and low *eclass* parameter values separately. Again we have considered a division into passive and star forming galaxies with the *eclass* threshold =  $-0.1$ . In the left upper panel of Figure 3 we show the fraction of star-forming galaxies for LSBGs in groups. As can be seen, we find a decrement in the fraction of star-forming galaxies at walls in comparison to the field. As it is expected, the fraction of star-forming HSB galaxies increases at the void walls (left lower panel of Figure 3), in agreement with the results from Figure 2. This is consistent with the relative changes in the fractions of blue and red galaxies of Figure 2.

Given our careful selection procedure and tests of uniformity of the local environment of the galaxies in our samples, we conclude that the behaviour of low fraction of blue, star-forming LSBGs is an intrinsic property of void walls. We argue that this can be associated to the transformation of void-wall LSBGs into star-forming HSBGs possibly due to the gas arriving from the void interior as a consequence of void expansion (we refer readers to Padilla et al. 2005, and Ceccarelli et al. 2006, for evidence suggesting that material from voids reaches walls). We will explore this and others scenarios in numerical simulations in a forthcoming paper.

## 4 CONCLUSIONS

We have performed a statistical study of the population of galaxies at void walls in comparison to the field. We studied their colors and spectral classes. Since these properties have been shown to depend on environment and galaxy luminosity, we made sure that the immediately local environment of void wall and field galaxies is the same, via a selection of host group masses, and luminosities so that their average values are matched. This selection allowed us to focus only on the effects of the global environment associated to the void walls. Our findings can be summarized as follows: i) There is a remarkable systematic decrease of blue, active star-forming LSBG fractions in groups at void walls, even when their luminosities and environment are the same. ii) Under the same conditions, we find an increase of the fraction of blue, active star-forming HSBGs at void walls. iii) There is also a mild decrease of the fraction of red, passive star-forming HSBGs at void walls. iv) We find no significant trend in the fraction of red, passive star-forming LSBGs at void walls, for galaxies with equal environment and luminosity.

## ACKNOWLEDGMENTS

This work has been partially supported by Consejo de Investigaciones Científicas y Técnicas de la República Argentina

(CONICET), the Secretaría de Ciencia y Técnica de la Universidad Nacional de Córdoba (SeCyT), GG is supported by Fondecyt regular 1120195 and NP by Fondecyt regular 1110328.

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